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The clearly observable behaviors that identify infant hand-use preferences make the development of this sensorimotor form of lateralization a valuable model for evaluating the development of other forms of lateral asymmetries of function. The current study examined the relation of individual patterns of development of handedness for reaching for objects (prehension) to the emergence of handedness in role-differentiated bimanual manipulation (RDBM). RDBM requires each hand to perform different, but complementary, actions on one or more objects. Hand-use preference for reaching for and grasping objects was assessed in a sample of 85 infants from the period of 6- to 11-months of age using a validated handedness assessment that consists of a series of presentations of 34 common infant toys. At 11 and 14 months, hand-use preferences for RDBM were assessed while the infants were involved in semiplay activity in which they were presented with a series of 13 toys (20-40 s for each presentation). Results revealed no significant relationship between prehension handedness and handedness for RDBM. However, multi-level modeling of the prehension data revealed interesting developmental changes in prehension handedness that can only be identified by using monthly sampling intervals with longitudinal methods.

DOES HANDEDNESS FOR PREHENSION PREDICT HANDEDNESS FOR ROLE-DIFFERENTIATED BIMANUAL MANIPULATION DURING INFANCY?

by

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CHAPTER I

INTRODUCTION

One unique characteristic of the human species is a right-sided bias in hand-use preference. Thus, human handedness raises two related questions: 1) how is it that during development each hand ultimately performs different skills; 2) how is it that the overwhelming majority of individuals prefer to use their right hand for the fine motor manipulation and exploration of objects and artifacts while the left tends to facilitate the actions of the right? This latter difference in hand actions is called "role differentiated bimanual manipulation" (RDBM) and has been proposed by some to be a unique characteristic of humans (Vauclaire, 1993). Since hand-use preferences emerge early in life (Michel, 2002), the search for ontogenetic answers to handedness questions can begin with the early manifestation of manual skills during infancy.

Since the lateralized behavior of handedness reflects hemispheric specialization of function, the investigation of the early development of handedness can provide insight into the early development of hemispheric specialization of function. Since atypical patterns of handedness (and underlying hemispheric specialization) may be related to specific neurobehavioral dysfunctions such as schizophrenia, autism, and mental retardation, the investigation of the early development of handedness may provide insight into the development of such neurobehavioral dysfunctions. Therefore, understanding the early development of hand-use preferences may provide valuable insight into how the lateralized organization of the brain develops and how disruptions of that development relate to neurobehavioral dysfunctions. Understanding the development of handedness may have important implications for understanding the development of the associated neurobehavioral dysfunctions.

What is handedness?

For nearly a century, neuropsychologists have attempted to employ handedness as an indirect measure of hemispheric specialization of function. As validation for such employment, many studies investigate the relationship between adult hand-use preference and other lateralized abilities including those involving cognitive processing strategies, emotionality, and language functioning. Unfortunately, most descriptions of handedness in adults are based on questionnaire inventories with no theoretical basis or valid empirical foundation and hence, these descriptions of handedness often provide little consistent evidence for their relationship to hemispheric specialization of function (Bishop et al., 1996). Identifying the most valid approach to assess handedness is difficult because there is no universally acknowledged clear-cut criterion of handedness against which to evaluate the validity of any assessment technique.

The most common form of assessment, the questionnaire, is often used simply for convenience (Bishop et al., 1996). Questionnaires are simple to administer (even to large groups) because they do not require any kind of equipment or even the presence of trained investigators (indeed, data can be collected on the internet). There is evidence to suggest that the preferences that individuals report on handedness inventories demonstrate a moderate degree of test-retest reliability, however there appears to be a decrease in reliability of inventory item data with increasing time between assessments (Ransil and Schachter, 1994). Furthermore, reliability of item scores appears to be highest for unimanual skills and much lower for more complex, bimanual skills. Although questionnaires may demonstrate overall reliability for a specific inventory, they provide researchers with little or no information about their validity as a measure of handedness (Bishop et al., 1996). Moreover, questionnaire assessments vary in their correlation with different performance measures.

Another common feature of questionnaires is the use of arbitrary cut-off points imposed on inventory responses in order to classify individuals into handedness categories. The variety of classification methods that have been applied in widely-used questionnaires have resulted in considerable variation in the reported proportion of individuals in each handedness category (Dragovic, 2004). Moreover, there are differing opinions about the specific number of categories that should be used to classify individuals. For example, although many questionnaires classify individuals into two discrete categories of right- and left-handed (e.g. Coren & Porac, 1978), an association analysis of Annett's (1970) 12 item inventory identified a minimum of eight classes and these appear to represent the degrees of hand preference along a continuum of right- to left-hand differences in skill. Thus, association analyses of binary (right or left) responses to an inventory with only 12 questions identified eight subgroups as the minimum number of categories of hand preference.

Alternatively, using a latent class model, Dragovic (2004) identified three discrete hand-preference clusters (i.e. left-, right- and mix-handed category) from an inventory with 10 items. Unlike Annett's questionnaire which used binary responses, participants in this study had their hand use preference recorded as left, indifferent, or right. Using a model-based approach that utilizes probability-based classifications, the author argued that further subdivision from 3 clusters of hand-preference resulted in a non-parsimonious subcategorization of individuals. That is, classification errors began to rise after a classification with three clusters indicating that models with more than three clusters of handedness were more likely to represent individual variations in responses across a variety of manual skills. Of course, increasing the number of types of items on a questionnaire and the sample size might generate more clusters.

Dragovic also assessed the contribution of each manual activity to the final classification of clusters. According to the information content index, some items were more informative than others. For example, items assessing bimanual activities such as the use of a broom, or opening a lid on a box (highly practiced activities that are not specifically trained), carried greater information content for the three latent class solution than unimanual activities such as writing or drawing (highly practiced but also specifically trained activities). In another study, Dragovic and Hammond (2007) applied the latent class model to Annett's 12 item questionnaire. Again, a three-class model of handedness was identified as the most parsimonious fit to the data. Interestingly, Flowers (1975) discovered four classes of individuals when he measured their performance on a unimanual, visually-controlled aiming task: right-handed, left-handed, ambidextrous (individuals whose performance with either hand was as good as the right hand performance of right-handed individuals), and ambisinistral (individuals whose performance with either hand was as bad as the left hand performance of right-handed individuals). Consequently, a three category handedness questionnaire would not relate well to Flowers' four categories of skilled performance handedness.

The differences between Dragovic's and Annett's classification procedures illustrate the difficulty in obtaining valid descriptive information on handedness from such self-report measures. Variations in the available responses for participants, classification procedures, and the types of skills assessed by the different questionnaires result in reported differences of the proportion of individuals in each handedness category. In addition, as Peters and Murphy (1992) contend, such models do not provide us with any certainty of whether the classification procedures distinguish between neuropsychologically meaningful subgroups.

Unfortunately, descriptions based on performance measures are subject to similar criticisms. Assessing manual proficiency is typically accomplished by measuring performance of the hands using one of several common tasks. These tasks include moving pegs along a pegboard, throwing objects at a target, marking dots in printed ovals (dot-filling) and fine manipulation measures such as finger tapping or writing. Although the list is not exhaustive, it provides an indication of the variety of measures (from those that are highly practiced and specially trained to those that are neither highly practiced nor specifically trained) that are often used to describe differences in manual performance. Establishing agreement between these various measures is difficult (Steenhuis and Bryden, 1999). For example, not all proficiency measures of handedness show similar distributions. Performance for moving pegs shows a right-biased normal distribution (Annett, 1985). For some other skills, the distribution appears to be bimodal. Using a dot-filling task, McManus (1985) found two distinct distributions that included right- and left-handers.

Investigators examining performance on both tasks using the same sample demonstrated similar results with a right-shift distribution for peg-moving and two distinct (left-right) distributions for dot-filling (Curt, Maccario, & Dellatolas, 1992). These findings suggest that the distribution of handedness depends heavily on the type of task adult participants are asked to perform. Note, however, that although both the peg-moving and the dot-filling tasks are neither highly practiced nor specially trained, they are unimanual tasks which do not capture a role-differentiated use between the two hands when simultaneously engaged in manipulation. Thus, regardless of whether an individual is considered a right- or left-hander, the skill level required to perform a task will play an important role in determining the degree to which strong differences in performance and skill are apparent. Consequently, the variability in criteria used for constructing classes of handedness contributes to the seemingly contradictory evidence about the relation of handedness to other variables (Michel, Sheu, & Brumley, 2002).

The quality of a manual skill depends on the nervous system's ability to generate a sequence of activations of the muscles in the arm that comprise the action. The pattern of neural impulses that control the action depends upon finely timed and serially ordered sequences of muscle activation. Therefore, measures of hand-use preference that directly depend on these attributes of manual skill may possibly reveal more about the organization of lateral biases in the nervous system than do more general measures of performance or performance outcome.

In order to determine hand-use preferences, assessments must focus on the patterns of organization and frequency of use for different types of skills and for skills of different complexity. For example, several studies have demonstrated that it is not uncommon for individuals, paradoxically, to prefer to use their non-preferred hand for certain tasks (Bryden et al., 1994; Harris & Carlson, 1993; Verfaellie & Heilman, 1990). Left-handers are more likely to engage in certain manipulatory actions (i.e. tightening a screw or opening the lid of a jar) with their non-preferred hand whereas the non-preferred hand of right-handers is more likely to be used to pick up objects (Steenhuis and Bryden, 1999). Gabbarb and Rabb (2000) argue that that the hand used during reaching may depend on the need for attention resources or the spatial information related to the particular task demands. During a well-practiced task in which the preferred hand becomes biomechanically constrained and whose use becomes no longer efficient, the non-preferred hand may be selected to perform the task. It is unclear whether the non-preferred hand is being controlled by the ipsilateral hemisphere, through callosal transmission of control, or whether, because the skill is so well-practiced, the ipsilateral hemisphere contains essential aspects of the motor programs needed for successful performance of the task. Hence, when assessing hand-use preference, it is important to address how task constraints, biomechanical variables, and neuromotor states combine to create patterns of movement.

Although the variety of measures used to assess handedness have led to seemingly contradictory evidence about the relationship between lateralization and other neuropsychological characteristics, developmental accounts of the trait that depend on patterns of organization and frequencies of use for different types of skills and for skills of varying complexity, as well as the relationship between different skills, can serve as a model for understanding the development of other forms of hemispheric specialization of function.

Hemispheric Specialization of Function

Understanding lateral asymmetries in the functioning of the two cerebral hemispheres has been a major focus for neuropsychologists interested in the relationship between brain organization and human behavior. Drawing on evidence from both clinical and nonclinical populations, a dominant view has emerged which argues that the two hemispheres are specialized to perform several distinctly different functions. This principle of hemispheric specialization of function relates to the more general modular notion of brain function (i.e., particular neural regions perform specialized computations that enable special functions). It is typically assumed that the computational specialization of the left hemisphere is essential for the manifestation of skilled movement and certain components of language. This organizational pattern appears to be well-established for right-handers and may be set early in development (Dehaene et al., 2002; Holowka & Petitto, 2002). Alternatively, the right hemisphere may be specialized for spatial skills such as the regulation of limb position and posture (Sainburg, 2002) or monitoring functions (i.e. processes that monitor sensorimotor inputs to ensure that motor outputs are congruent with the intended motor action). These monitoring functions are apparent when there is a mismatch between motor intention and proprioceptive and/or visual feedback (Fink et al., 1999).

Although these views have traditionally served as the dominant perspectives in the study of hemispheric specialization, more recently, researchers have begun to propose that the development of lateralization of function is a dynamic process in which the functional contribution of both hemispheres is more flexible and influenced by several fundamental factors (Serrien, Ivry, & Swinnen, 2006; Shabbott & Sainburg, 2008). For example, Amunts et al. (1997) observed interhemispheric differences in the structural development of primary motor cortex. These experience-dependent asymmetries in the cytoarchitecture of the cortex differ from adult patterns and are likely associated with the functional development of motor skills and handedness. In addition, there is considerable cortical plasticity during early development and following injury that appears to be experience-dependent (Kolb & Gibb, 2001). Such plasticity would permit experiential factors to modify or shape the development of functional asymmetries.

Interhemispheric differences may also arise from the differential sensitivity of the hemispheres to spatial frequency information. That is, any processing requiring a high level of sensory and motor resolution likely will engage the left hemisphere, whereas any processing of low-resolution information is likely to involve the right hemisphere (Sergent, 1982). These findings indicate that the relative contribution of each hemisphere is not static but dynamically shaped by experiences during development. An important issue for research is to identify how specific experiences shape such development.

For the current study, it is likely that experiences associated with the development of a hand-use preference for prehension may contribute to the development of hand-use preferences for RDBM. Infants with stable hand-use preferences are likely creating sensorimotor experiences that are quite distinct from those without a stable hand-use preference. If callosally mediated interhemispheric communication is absent during early infancy, as has been demonstrated by electrophysiological and behavioral evidence (Cernacek & Podivinsky, 1971; Salamy, 1978), then certain forms of haptic experience associated with manual exploration would be confined to one hemisphere. For example, during early infancy, acquisition of an object is typically followed by the action of bringing the object to the mouth. The hand that acquired the object continues to actively explore the object as it is mouthed. Although haptic information is being sent to both hemispheres from the feedback associated with mouthing (Rose, 1984), only the hemisphere contralateral to the hand holding the object is receiving information simultaneously about the sensory consequences of mouthing and manipulating the object. Therefore, the hemisphere contralateral to the hand holding the object to the mouth is receiving different types of perceptual information from that received by the opposite, passive hand. These differences in experience may, in turn, have consequences on the "programming" of actions for how the hands can be employed with object manipulation.

The distinct experiences provided by proprioceptive and haptic feedback to the two hemispheres could lead to differences in how each hemisphere may program and execute manual skills. Indeed, it has been demonstrated that infants with longitudinally stable hand-use preferences can possess and manage objects more effectively than those without a hand-use preference (Kotwica, Ferre, & Michel, 2008). It is possible that a hand-use preference facilitates the coordination of the two hands during complex sequential actions such as those involved in the management of multiple objects. Moreover, asymmetrical bimanual actions may be coordinated in a manner such that the preferred hand (and by extension the contralateral hemisphere with differential sensitivity to haptic information) is the hand that ultimately engages in the active exploration of an object during a role-differentiated action. Consequently, prehension handedness ought to predict RDBM handedness.

It has long been acknowledged that some variability exists between handedness and hemispheric specialization of function (Annett, 1975). Right handedness has been proposed to be a consequence of those processes underlying the left hemisphere's control of movement and language. The left hemisphere's dominance for skilled movement has been said to result from anatomical and functional asymmetries of the primary cortex and descending pathways (Amunts et al., 1996; Volkman et al., 1998) as well as to secondary motor and association areas (Haaland, Harrington, & Knight, 2000). It has also been suggested that excitability of corticospinal pathways in right-handers is higher for the left than the right hemisphere (De Gennaro, 2004). The ability to manifest sequential actions does seem to depend on the left hemisphere for both the left and right hand (Haaland, Elsinger, Mayer, Durgerian, & Rao, 2004) and the left hemisphere contributes significantly to actions that involve the planning of sequences based on response selection, preparation and/or retrieval (Schulter, Rushworth, Passingham, & Mills, 1998; Verstynen, Diedrichsen, Albert, Aparicio, & Ivry, 2005).

Evidence for the left hemisphere's involvement in the programming of movements also comes from clinical cases of individuals with brain lesions. The consequence of pathology to the left hemisphere is manual apraxia, a condition in which individuals demonstrate difficulties in performing movements with the hands and arms. The disturbance tends to occur in the absence of motor weakness and impairs movement bilaterally.

For example, Kimura and Archibald (1974) presented a series of novel hand and arm movements for immediate reproduction by patients with left- or right-hemisphere damage. The movements produced by the researchers varied across a range of hand postures, arm positions, and orientations in relation to the body and shared no resemblance to known gestures or other learned movements. Deficits in the group of patients with left-hemisphere lesions were remarkably pronounced in comparison to a group with right-hemisphere lesions suggesting that the left hemisphere is responsible for the selection and production of movement sequences. Interestingly, performance of unfamiliar movements like those described above and familiar kinds of movements was highly correlated indicating that a similar mechanism may account for movement selection in both types of gestures. Kimura (1993) concluded that the finding that the left-hemisphere lesions had at least as marked an effect on the imitation of unfamiliar meaningless movements as on the production or copying of well-practiced movements indicates the left-hemisphere praxis system is essential for selecting various types of movements or postures of the arms and hands. Such a system may play an important role in the acquisition of novel motor skills.

According to Kimura, there is also significant overlap between the manual praxis system and systems responsible for organizing multiple oral movements and speech. Non-verbal oral-movements (including those that utilize the muscles responsible for moving the tongue, jaw, and lips) parallel the characteristics of oral-movement control that is involved in speech. For some speech disorders, the consequence of a lesion does not typically result in errors at the articulatory single-syllable level, but rather when integrating finely-timed and serially-ordered units into connected speech (Kimura, 1993). In order to test the notion that analogous non-speech oral-movement defects would be present when a sequence of movements is to be produced, Kimura & Watson (1989) measured performance on imitation of oral movements by patients with lesions localized to the anterior, central, or posterior sectors of the brain.

In one task, patients were required to imitate a series of relatively simple single movements (i.e. positioning the tongue on either side of the mouth, blowing, chattering teeth) presented one at a time for immediate reproduction. The second task consisted of patients being asked to imitate a sequence of three different oral movements for each trial. Patients with left anterior damage demonstrated the greatest impairment in producing single oral movements. Patients with lesions to left posterior regions, although performing worse than patients with right hemisphere damage, were much more capable of imitating single oral movements. However, patients in the left posterior damage group had severe difficulty in imitating a sequence of multiple oral movements,. Thus, it appears the posterior region plays an important role in selecting movements which is apparent when more than one movement can be an alternative in a sequence. Performance on the same multiple oral-movement task has been shown to be highly correlated with the manual movements described earlier in this section. Kimura (1993) concludes that a similar mechanism may account for actions that involve multiple oral movements (similar to those used during the production of fluent speech) and sequences of manual movements. That is, some aspects of oral and manual control may depend on similar neural circuits.

Ramsay (1980, 1984) provided further support for this argument by demonstrating that the onset of unimanual hand preference appears during a developmental stage in which duplicated syllable babbling occurs in infants, whereas bimanual hand preference coincides with the onset of nonduplicated (multisyllabic) babbling. Therefore, the left hemisphere in many individuals is likely important for the selection and execution of articulatory/motor acts for both speech and non-speech movements. Thus, it is possible that the processes that make the left hemisphere dominant for certain language functions (including the coordination of finely timed, well-executed motor actions involved in speech) serve an important role in skilled manual actions.

The typical notion is that the left hemisphere is "prepared" (by genes) to control speech functions and that incidentally makes it more likely to control hand-use preferences (Annett, 1975). However, it also is likely that the early development of hand-use preferences during infancy contribute to the development of hemispheric specialization to control speech (Michel, 1988). Since the development of neural organization involves a continuous reciprocal interaction between current states of the nervous system and the experiences provided to it by the actions that it creates, developing hand-use preferences ought to be influencing the organization of the nervous system. The left-hemisphere may be more involved in the planning, organizing, and executing of fine motor functions thereby making the manifestation of hand-use preference and differential proficiency and skill between the two hands both a valuable example of, but also contributor to, further hemispheric specialization of function underlying the manifestation of speech (Michel, 1988).

A major weakness of approaches to the study of hemispheric specialization is disagreement on how the functional differences between the hemispheres should be described. Many of the descriptors used (e.g. "analytic versus holistic" or "verbal versus spatial") provide little insight into the mechanisms of the nervous system that underlie lateral asymmetries of behavioral functioning. Hemispheric specialization must be described by clearly identifiable concepts before theories of the development of hemispheric specialization of function can be evaluated. Since manual specialization has been demonstrated to have an empirical relationship with other forms of hemispheric specialization of function, systematic characterization of the development of handedness and other forms of manual specialization could provide more useful information about the organizational features of each of the hemispheres.

It has been proposed that hemispheric specialization of movement control is established early in infancy and hand-use preferences during this period may contribute to that specialization (Michel et al., 2006). If such is the case, then it is likely that those individuals, who as infants demonstrate a distinctly different profile of hand-use preference, may exhibit a different pattern of hemispheric specialization, especially as this contributes to the acquisition of new skills as children or adults. For example, infants with a consistent left hand-use preference during infancy may not exhibit the same pattern of hemispheric contribution to the establishment of expertise in motor skills that has been consistently identified in right-handers. Furthermore, infants who are slow to develop hand-use preferences may not exhibit the same pattern of hemispheric specialization of function as those who developed an early hand-use preference.

Since the development of hemispheric specialization may be occurring within the context of the emergence of callosal functioning the patterns of hemispheric specialization present early in development may depend greatly on the absence or presence of interhemispheric collaboration during motor actions (Ramsay, Campos, & Fenson, 1979; Diamond, 1991; Fagard et al., 2001).. These assumptions merit further exploration as a thorough understanding of the organizational features of handedness may reveal the nature of their relation to language and other lateralized functions.

Interhemispheric Communication

Handedness and other forms of hemispheric specialization of function tend to require interhemispheric communication to coordinate the unity of functioning. Movements, especially bimanual movements, which emerge from the lateralized functions of both hemispheres, require that information be integrated to produce a synchronized motor pattern. For example, tying shoe laces, using a fork and knife, or buttoning a shirt require the integrated and sequenced actions of the two hands with a finely timed transition between actions across hands. Typically, each hand is assigned a role with the non-dominant hand serving as the support, or postural role. Given that these types of motor skills demand each hand follow a complex spatiotemporal pattern such that the movement onset and trajectories for the two hands are not symmetrical but are nonetheless highly coordinated, the presence of role-differentiated bimanual skills provide some indication of interhemispheric collaboration. Thus, the character of role differentiated bimanual skills may be a useful marker of the efficiency of callosal functioning (Kimmerle, Mick, & Michel, 1995; Wolf, Michel, & Ovrut, 1990). For movements that draw on functions lateralized to one hemisphere or the other, efficient gating of movement is vital. Such interactions can occur via the corpus callosum, allowing for the transfer of the planning, feedback, and contextual input that guide movement selection (Geffen et al., 1994; Ellenberg & Sperry, 1980). Callosectomized patients suffer from a variety of deficits, including impairments in prehension that are due to a lack of callosally mediated communication between the two hemispheres. For example, sectioning the callosum impairs the left hemisphere's ability to control the left hand and the right hemisphere's ability to control the right hand (Gazzaniga et al., 1967). Ipsilateral sensory-motor combinations are dependent upon the intact callosum in order to integrate information from the cortical sensory areas to the motor cortex that controls hand movements. Prehension, or the act of reaching towards an object and grasping it, requires the activity of both the proximal musculature to transport the arm to a specific location and the distal musculature to adjust the shape of the hand to the characteristics of the target (Jeannerod, 1981). The deficits seen in callosectomized patients are more pronounced for the distal hand movements as opposed to the movements guided by the more proximal musculature of the shoulder and arms (Gazzaniga, 2000). Therefore, a skill such as the apprehension of objects requires the interaction of circuits lateralized to ipsilateral and contralateral hemispheres.

The range of functional distinction that characterizes the differences between the hemispheres in motor control likely emerges during early development. Bimanual coordination improves extensively during late infancy and early childhood (Kimmerle, Mick, & Michel, 1995; Fagard and Corryer, 2003) and improvement in the coordination of asymmetrical movements of the two hands in early childhood is related to improvement in interhemispheric communication (Fagard, Hardy, Kervella, & Marks, 2001). Fagard et al. used a task like an "etch-a-sketch' in which a sample of 5- to 10-year old children had to create 45° sloping lines by cranking in phase with each hand or at a 180° out of phase movement. Failures during the RDBM out of phase task were the consequence of mirror movements by the two hands, That is, failures occurred because one hand duplicated the action of the other when it should not have.

Developmental progress in bimanual coordination (as evidenced by fewer mirror movements) co-occurred with improvement in the ability to transfer perceptual information. This ability was determined by the latency of a manual response to a visual stimulus presented tachistoscopically to the left or right hemisphere. This tests interhemispheric communication when the hemisphere receiving the stimulus is ipsilateral to the hemisphere controlling the manual response. When latency to respond improves, it is suggested more efficient interhemispheric communication has occurred. Older children demonstrated a much shorter latency to manually respond to visual information presented to the ipsilateral hemisphere. Older children were also more proficient at producing parallel movements in a line drawing task. Mirror movements, also described as “in-phase” manual patterns, are a strong attractor for bimanual rotation, whereas parallel movements or “anti-phase” patterns are more difficult to coordinate (Kelso et al., 1983). Thus, improvement in the children’s ability to produce parallel (or nonmirror) movements is likely to be dependent upon interhemispheric communication in order to resist attractions to an “in-phase” pattern. However, it is also likely that bimanual actions contribute to improvements, as much as reflect, the development of such interhemispheric communication (Kimmerle, Mick, & Michel. 1995).

Inhibitory interactions in adults may also be necessary during the preparation of unilateral actions to counteract the production of default mirror movements (Duque et al., 2005); that is, inhibition prevents the involuntary movements of one hand that accompany the voluntary actions of the other hand. Using transcranial magnetic stimulation, Netz et al. (1995) demonstrated that in right-handers inhibitory effects between both motor cortices are greater from left to the right hemisphere than vice versa - a functional distinction that may contribute to hemispheric specialization in motor control. Consequently, it is likely that functionally adaptive motor behavior is dependent upon inhibitory processes that may help to exploit the processing benefits associated with hemispheric specialization (Serrien, Ivry, & Swinnen, 2006).

Bimanual skills require the formation of trajectories coupled with temporal coordination to perform a series of finely timed and sequenced set of events. This includes control of the timing and magnitude of activation of various muscles. Callosal interactions may serve as the functional basis for crosstalk between the motor plans for the two hands (Cardoso de Oliviera et al., 2001). In addition, mechanisms of information gating across the corpus callosum are necessary for tasks involving response selection (Hazeltine, Diedrichsen, Kennerley, & Ivry, 2003). Therefore, facilitation processes that permit the integration of information across both hemispheres may assist in capitalizing on the advantages associated with hemispheric specialization.

Transfer of information between the two hemispheres is essential when their respective processing is required to successfully complete a movement such as one that involves role-differentiated actions between the two hands. For example, Shabott & Sainburg (2008) propose that the dominant hemisphere is required for coordinating efficient trajectories while the non-dominant hemisphere is specialized for controlling limb impedance, as required for maintaining stable postures. In order to execute a movement in which the nervous system must coordinate asymmetrical, yet finely-timed and sequential actions for the two hands, information about the trajectories of the two hands must be integrated with information about a steady state limb position. Callosally mediated mechanisms may serve as the basis for incorporating information from these specialized but distributed regions.

Understanding the development of this type of organization is important because specific developmental disabilities have been linked to dysfunctional integration among neural circuits (Serrien, Ivry, & Swinnen, 2006). For example, Friston (1998) argues that schizophrenia may result as a failure of integration between functionally specialized systems required for adaptive sensorimotor integration and cognition. It also has been suggested that impaired hemispheric transfer of sensory and motor information is prevalent among dyslexics (Habib, 2000). Thus, understanding the development of hemispheric interaction may be vital for understanding the development of bimanual actions in normal children as well as clarifying the role it may play in developmental disabilities.

The connections between the two hemispheres mature progressively during the first decade of life. According to electrophysiological and anatomical studies, the major fiber bundle that comprises the corpus callosum is among the last systems to complete myelination (Farber & Knyazeya, 1991; La Mantia & Rakic, 1984; Salamy, 1978; Hagelthorn, Brown, Amano, & Asarnow, 2000). Fagard et al. (2001) argued that increased interhemispheric communication is a major factor influencing bimanual coordination of non-mirror movements and may thus contribute to developmental progress in bimanual coordination. If effective communication between the two hemispheres permits the development of expertise in bimanual coordination, then it is necessary to investigate bimanual skills as they emerge in their earliest forms during development. Goldfield & Michel (1985) demonstrated that by 11 months of age, bimanual reaches are no longer linked by a close temporal or spatial relationship of the hands - such unlinking would permit the expression of role-differentiated bimanual skills. Thus, examining the patterns of bimanual hand-use during infancy may allow us to identify the developmental precursors of manual skills that may reflect both hemispheric specialization and interhemispheric collaboration.

Handedness during Infancy: Stable or Variable?

Because of the cumulative properties of development, the developmental origins of any characteristic can extend far back in to an individual's life history (Michel & Moore, 1995). Thus, any developmental achievement is a consequence of both the events that precede its occurrence and a structure of historically derived causal relations. Describing the emergence of a trait requires detailed descriptions of the precursors that served as foundation for the trait. Therefore, a thorough understanding of handedness in the adult form depends on systematic characterization of the period during which the foundations of the trait are established—that is, during infancy. Although some researchers argue that handedness cannot be identified until early childhood (Janssen, 2004), there is growing evidence to suggest that infant hand-use preferences for a skill such as prehension are relatively stable for a majority of infants in the age period as early as 7 to 13 months (Michel et al., 2006). By separately assessing preferences for various manual skills, reliable patterns of hand-use can be identified in infants that would permit the comparison of infants without a hand-use preference to those with a hand-use preference.

Variability in the use of a preferred hand after the acquisition of a skill such as prehension has been noted in various longitudinal studies (Thelen, Corbetta, & Spencer, 1996; Fagard, 1998; McCormick and Maurer, 1988; Corbetta & Thelen, 1999; Piek, 2002). However, the type of variability exhibited across studies is dependent upon the method used to assess handedness. For example, Fagard and Lockman (2005) described differences in the choice of one particular hand or of a one-handed versus two-handed strategy during object grasping and exploration in children from 6- to 48-months of age. According to the authors, task constraints influence the expression of handedness. For reaching tasks that required precision, the variability of hand-use decreased with the right hand clearly being preferred by a majority of the infants in each of three different groups (6-12 months of age, 18-24 months of age, and 30-36 months of age). For objects that afforded several possible explorations, variability in the hand used for grasping increased. In addition, when grasping involved bimanual manipulation, hand-use preference emerged more clearly for 18- to 36-month-old infants. Other studies report differences in the trajectories of infant reaches. The number of peaks in the hand-speed profile of infants is argued to reflect the uncontrolled dynamics of the arms (Thelen et al., 1993) or the presence of multiple action or movement units (von Hofsten, 1991). According to von Hofsten, the number of peaks decreases with age, whereas Fetters and Todd (1987) found that the number of peaks is relatively stable with age. Such inferential differences demonstrate that descriptions of instability in infant handedness may refer to rather distinct patterns of variability. Furthermore, as Berthier and Keen (2006) contend, although the studies provide dense longitudinal data, the number of infants in each sample is very low (Thelen reported data from 4 infants whereas von Hofsten used a sample of 5) thus limiting the ability to generalize from the results.

Given the variability in methodologies and the limits of small sample sizes, it is no surprise that the conventional conclusions about handedness during early development state that the trait is neither reliable nor stable until sometime between the ages of 6 and 10 years (Janssen, 2004). However, handedness may appear as unstable and variable during infancy because of variation in the types of skills being assessed as opposed to reflecting some underlying instability of the infant's handedness status. Different manual skills are acquired at different ages and each may exhibit unique patterns of expression during development (i.e., developmental trajectories). Therefore, handedness must be assessed separately for several manual skills (Michel, 1988). Comparison of hand-use preferences among several manual skills within and across age groups may provide a more complete description of infant handedness status that avoids confounding developmental changes in handedness with developmental changes in manual skill.

Assessing Handedness during Infancy

According to Michel, Ovrut, and Harkins (1986), any valid and reliable description of handedness in infants within the age range of 6- through 13-months must include an assessment technique that measures hand-use preferences in various manual skills including: reaching for and apprehending objects (prehension), differences between hands in manipulating objects (unimanual manipulation), and the coordination of complementary bimanual actions (role differentiated bimanual manipulation - RDBM). RDBM is a skill in which each hand performs a different action, but the actions coalesce in the manipulation of an object. That is, the actions of the two hands have different but complementary functions; one hand supports or stabilizes the object while the role of the other hand is to manipulate or explore the features of the object. Each of the skills has been shown to reveal infant hand-use preferences and follow different developmental patterns during this age period. Prehension becomes a well established sensorimotor skill by 5 months of age and hand-use preferences for this skill can be identified as early as 6-7 months of age (Michel, Ovrut, & Harkins, 1986). Unimanual manipulatory actions become a common form of infant manual activity during the period of 6 to 11 months and unimanual manipulation preferences emerge by 7-8 months; however, the range of actions for which this preference is expressed continues to grow during the first year (Hinojosa, Sheu, & Michel, 2003). Complementary bimanual actions are not well-established until 11 to 12 months and RDBM preferences do not manifest until the period from 12 to 13 months (Ramsay, 1979; Kimmerle, Mick, & Michel, 1995). Individual assessment of these various manual skills as well as any relationship that may exist between the skills provides a clearer picture of the developmental changes that occur in infant handedness.

Another important consideration in the assessment of infant handedness is the manner in which preference is defined. A hand-use "preference" can refer either to a simple difference in use between the hands (Ramsay, 1980) or to statistical estimates of whether the intermanual differences are unlikely to have occurred by chance (Hinojosa, Sheu, & Michel, 2003). With a sufficiently large enough set of items for assessing handedness (~28 instances for frequency data), binomial or approximations of normal distributions can be used to determine whether the infant's apparent preference for using one hand more than the other at that time would have occurred by chance. Longitudinal studies (e.g. assessments at monthly intervals from 6- to 14-months of age) may be treated either as "samples" of the infant's handedness status taken at different ages or as a basis for identifying trajectories in handedness development. The former approach provides data that reduce sampling error and increase the reliability of an individual's assessment (Michel, Sheu, Tyler, & Ferre, 2006). In the latter, using statistical estimates of the reliability of the preference for each age permit identification of nonlinear trajectories as opposed to "instability" of development. Therefore, statistical decision criteria offer a more reliable way to determine whether an identified preference may reflect an underlying difference in manual skill that is unlikely to have occurred by chance.

Developmental studies must begin with descriptions of the characteristics of handedness from its earliest manifestations. In order for these descriptions to have any theoretical value, they must be based on reliable and valid techniques for assessing an individual's handedness status. As noted above, a stable characteristic revealed by many studies is that an infant's status appears to be rather different at different ages. That is, the expression of hand-use preferences at one stage may exhibit different patterns than a hand-use preference in subsequent stages. A handedness status that manifests itself in the form of various manual skills (i.e. prehension, unimanual manipulation, and RDBM) is likely to be organized differently from one that is manifest only during prehension (Michel, 1988). Therefore, infant handedness assessments must provide ways of identifying how the mechanisms underlying the organization of hand-use preference at one stage are derived from earlier conditions and processes. By using an assessment technique that measures hand-use preferences for various manual skills and one that identifies the preferences based on statistical decision criteria, such developmental patterns can be described.

Current Study

Using an empirically reliable and validated method of assessing handedness (Michel, Ovrut, & Harkins, 1986), the aim of the present study was to describe the relationship between two manual skills present during infancy: prehension and role-differentiated bimanual manipulation. As noted above, in order to achieve a thorough understanding of infant handedness, manual skills must be assessed individually as well as in relation to one another. Thus, the present study longitudinally examined whether a hand-use preference for prehension established in the period from 6-11 months predicts a preference for role-differentiated bimanual manipulation at 11 and 14 months of age.

Role-differentiation emerges after an infant has acquired competency with unimanual grasping. By 11 months of age, the spatial and temporal patterns of movement of both hands have changed in ways suggesting movement of each hand is separately controlled and coordinated thereby permitting the hands to exhibit distinctive roles during bimanual exploration of objects (Goldfield & Michel, 1985). Coordinated actions involving clear role differentiation between the hands are present by 1 year of age and appear to be lateralized, with the preferred hand assuming the manipulating role (Michel et al., 1985). However, many studies reveal differences in the age at which RDBM is present. For example, Fagard & Jacquet (1989) observed complementary bimanual actions as early as 9-10 months of age. For certain objects that require the hands to perform asymmetrical yet complementary functions, RDBM may not appear until 17 to 24 months of age (Ramsay & Weber, 1986; Fagard & Jacquet, 1989). Kimmerle et al. (1995) observed that RDBM, present in a majority of infants at 13 months of age, can be elicited by specific object characteristics as early as 7 months. Interestingly, the Kimmerle et al. study demonstrated that variations in the characteristics of the toys used for assessment and/or measurement protocol account for differences in age at which the action can be observed. Moreover, sequential analyses of the actions that ended in RDBM exhibited no reliable pattern until the infants were 13 months of age (Kimmerle, Ferre, & Michel, in prep) making it likely that the earlier forms of RDBM were not programmed by the nervous system but emerged from the constraints created by characteristics of the objects and the infants' manipulation skill. Therefore, infants must be provided with a range of toys that differ in their characteristics (i.e. sounds or movable parts) to permit the expression of different patterns of role differentiation.

The RDBM skill is of developmental interest because it seems to represent: 1) a transition in perceptual-motor skills; 2) comprehension of object function; and 3) knowledge of the physical characteristics of objects. In addition, role-differentiation requires integration and sequencing of separate motor acts between the distal parts of the limbs (hands and fingers)--a process that reflects both hemispheric specialization and interhemispheric collaboration. Bimanual coordination appears to depend on the development of the supplementary motor areas (SMA) of left and right frontal cortices and their interconnection through the corpus callosum (Diamond, 1991). However, the presence of role differentiation as early as 7 months may reveal something about the underlying relationship between bimanual coordination and the maturation of SMA. The earliest forms of role-differentiated bimanual manipulations do not require great skill (i.e. speed, precision, proficient grip, or strength) and may occur in the absence of callosal involvement. Thus, it is possible that these early manifestations of role-differentiated bimanual manipulations contribute to, as well as reflect, the functional development of the corpus callosum and the SMA (Kimmerle et al, 1995). RDBM and its relationship to earlier prehension preferences may also reveal something about the developmental processes by which earlier forms of lateralized functions concatenate into subsequent forms.

According to Michel (1998), handedness develops from a cascade of events beginning with a neonatal bias in the direction of head orientation which, in turn, results in a greater amount of ipsilateral hand and arm activity (that creates a greater amount of visual and proprioceptive feedback for the side to which the infant's head is turned). This feedback provides visual-manual and manual-body spatial "maps" that can be used to program arm movements to the appropriate spatial location to apprehend seen or felt objects. Hence, the consequence of a neonatal bias in supine head orientation in turn leads to a preference for apprehending objects. Since the majority of infants manifest a rightward head orientation preference, the majority of infants will exhibit a right hand-use preference for prehension. Those infants with a leftward head orientation bias develop a left hand-use preference for prehension (Michel & Harkins, 1986). The grasping preference affords increased opportunities for visual and haptic-motor feedback of the obtained objects. Thus, infants who exhibit a consistent hand-use preference for prehension develop a bias for unimanual manipulation activities that represent the same hand preference that they exhibit when reaching for and grasping objects (Hinojosa, Sheu, & Michel, 2003). The present study will determine whether early lateral biases for prehension predicts (and theoretically contributes to) subsequent lateral biases in RDBM.

Michel et al. (2006) demonstrated that a majority of infants will exhibit a consistent hand-use preference when reaching for objects during the seven- to thirteen-month age period. Among those infants that exhibit a consistent preference, an overwhelming majority prefer to use the right-hand to acquire objects (~ 40%) whereas only a small proportion prefer to use the left hand to acquire objects (~17%). In this study, prehension preferences for a sample of infants during the 6- to 11-month period were identified. It was hypothesized that the majority of infants would exhibit a clear hand-use preference. By basing the study on a large enough sample, we attempted to identify infants for three different groups: infants with a left, right, or no hand-use preference for acquiring objects. These categories of prehension preferences could then be used to compare infants' patterns of RDBM.

Therefore, a goal of the study was to identify a potential predictor of hand-use preference for RDBM. An infant's hand-use preference for prehension predicts the later emergence of a hand-use preference for manipulating objects (Hinojosa, Sheu, & Michel, 2003). That is, an infant's hand-use preference for obtaining objects can contribute to the development of a hand-use preference for manipulating objects. Such consistency of hand-use preference across the skills likely reflects a developmental cascade of events in which a hand-use preference for a skill that emerges earlier in development contributes to hand-use preferences for skills that emerge later in development. Thus, it was hypothesized that those infants that exhibit a clear preference for prehension during the six- to eleven-month age period would exhibit a hand-use preference for RDBM that represents the same hand they preferred to acquire objects with. That is:

1. Infants will exhibit little or no hand-use preference in RDBM at 11 months of age but by 14 months of age, most infants will exhibit a hand-use preference in RDBM, with right-handedness predominating.

2. Infants that prefer to acquire objects with the right hand during the 6- to 11-month age period will exhibit a preference to manipulate the features of an object with the right hand while engaged in RDBM during the 11- to 14-month age period;

3. Infants that prefer to acquire objects with the left hand during the 6- to 11-month age period will exhibit a preference to manipulate the features of an object with the left hand while engaged in RDBM during the 11- to 14-month age period.

4. Those infants who do not exhibit a hand-use preference for prehension during the 6- to 11-month period will not exhibit a hand-use preference for RDBM

CHAPTER II

METHODS

Research Participants

85 infants (44 male and 41 female) were recruited using birth records of the Guilford County Court House. These publicly available records were used to contact the mothers via mail with a letter describing the study. Interested mothers were asked to reply by telephone or email so that any questions could be answered, to solicit their infant's participation, and schedule a time for their baby's visit to the laboratory. Mothers were also questioned about their pregnancy and delivery in order to ensure all infants included in the study were from full-term pregnancies with uncomplicated births. Full-term pregnancies were considered those that had a gestation period of 37 weeks or greater.

Upon agreeing to participate, parents were asked to bring their babies to the lab within 7 days of the infant's birthday beginning at 6 months of age. Each infant was assessed once a month from 6 to 14 months of age. Parents were informed that they would receive a $10 gift certificate as compensation for each of their visits to the laboratory. Given the population of Greensboro, we were able to recruit infants that represented a diverse mix of ethnic backgrounds including Hispanic, African American, and Asian. The procedure for recruitment, obtaining informed consent, data collection and presentation were in accordance with the regulations set by the Institutional Review Board for the protection of human subjects.

Apparatus

Thirty-four common infant toys were used for the handedness assessment. The toys selected for the study are brightly colored, easily grasped, and contain features that produce noise or movable parts that increased the likelihood that the infants would reach for them and engage in some form of exploration. For 10 out of the 34 presentations, pairs of identical toys were used to provide the infant with the option of using both hands to reach for and obtain a toy. Furthermore, 13 of the toys selected for the study potentially afforded complementary bimanual hand use. That is, the characteristics of the toys were such that the infants could support the toy with one hand while the opposite hand engaged in manipulatory activity of the features of the toy. These toys are capable of being grasped by one hand and are similar to the set described by Kimmerle et al. (1995). The toys differ in their range of physical characteristics which include movable parts, “grasp-ability”, and finger control. The “movable parts” characteristic distinguishes single, solid-piece toys from those that contain movable features (i.e. rings around a rattle). Grasp-ability refers to the ease or difficulty with which the toy can be acquired by the infant. Although all the toys can be grasped by the infants, the size, shape and weight of some the toys make them slightly more difficult to hold. Finally, finger control identifies toys that afford some kind of fine motor exploration such as a single finger or pincer action. The toys ranged from those with no movable parts that do not require finger control and can be easily grasped to toys with movable parts that require fine motor finger control and are more difficult to grasp.

For the assessment, the infant was seated on the mother's lap at navel height to a table. At this height, infants were able to have their arms completely above the table so that any reaches or limb movements were not constrained. Mothers were also asked to sit as close as possible to the table so that the infants maintained a steady posture. All of the infants' manual actions were recorded using two Panasonic digital cameras connected to a Videonics mixer and recorded on a Panasonic DVD recorder. One camera was placed directly overhead and the other to the right of the infant which permitted two different views of the presentations. The mixer and DVD recording provided split screen capability so that simultaneous recordings of the two camera feeds could be obtained. These recordings were transferred to a computer containing the Noldus Observer software for coding video.

Procedure

While the infant was seated on the mother's lap, a validated handedness assessment for apprehending objects was administered (Michel et al., 1986). The test was administered to the infant once a month from 6- to 11-months of age. The assessment consisted of the separate presentations of 34 toys. In order to ensure that task constraints did not play a significant role in the hand used to acquire objects, a variety of presentations were used. 10 involved the presentation of two identical toys, each in line with the infant's shoulders, either on the table (7 pairs) or in the air (3 pairs). 24 involved the presentation of one toy in line with the infant's nose, either on the table (19 toys) or in the air (6 toys). Because of their various movable parts, 3 of the single toy presentations were presented twice. By varying the type of presentation (i.e. in the air or on table; single or double toys) and providing sufficient degrees of freedom in task constraints, the assessment is less likely to be influenced by biases that may occur as a result of task constraints.

Each presentation was video-recorded for 15 seconds after which the toy was removed from the infant's hands. Each infant received the same order of toy presentations which represented increasing complexity in the features of the toys and variability in the types of actions necessary for obtaining and manipulating the toy. After every 3 presentations, or if the infant's posture was biased so that they were slightly turned, the presenter tickled the palms of the infant and positioned them straight with the table to prevent any bias in reaching and to ensure continued activation of the hands. Tickling the palms of the infants and positioning them evenly with the table limits the influence of biomechanical variables (such as postural influences on limb use) and habitual reaching patterns that can occur as a result of repeated use of the same limb to obtain the object.

Parents were instructed not to interfere with the play. For the instances where this could not be avoided, the data was excluded from the presentation. The complete assessment lasted about 35 minutes. In cases when infants began to cry or becomes fussy, a short break was taken so the infant could return to an alert/active state. Infants must be in an alert/active state to avoid any confounds that may be a consequence of the infant's neuromotor state (i.e. attempting to acquire objects during a fussy or crying state).

Assessments of role-differentiated bimanual manipulation (RDBM) preferences were conducted at 11- and 14-months of age. Again, the tests were administered each month using an adaptation of a RDBM assessment described in Kimmerle et al. (1995). The seating arrangement and recording procedure was similar to the one described above. The assessment consisted of 13 toys, each with at least two parts that could elicit differential hand-use. Because two of the toys had various movable parts, they were presented twice for a total of 15 presentations. The series of toys has been demonstrated to reliably elicit role-differentiated actions by an overwhelming majority of infants by 11-months of age (Kimmerle et al, 1995) although few exhibited a hand-use preference in RDBM.

Eight of the ten toys used in the Kimmerle et al. assessment were used for the current study. In addition, five new toys were added to the assessment. All of the toys provide a range of characteristics that can be used to assess different patterns of RDBM. Only single toys were used based on the assumption that these are motorically less complex than those involving multiple-toy manipulations and therefore would facilitate early demonstrations of role-differentiation. However, two of the toys consisted of two separate parts that permit the insertion of one object into another. Each toy was presented at midline (in line with the infant's nose) after the presenter demonstrated the RDBM action that the toy affords. In contrast to the prehension tasks, each infant was provided with additional time during each presentation in order to ensure that bimanual manipulations would occur. The infant was allowed to manipulate the toy for at least 20 seconds or until he/she terminated the presentation.

The toys selected for this assessment included toys with different shapes, a variety of different types that produce different effects (i.e. spinning parts, pushable buttons), toys that make various sounds, as well as toys that produce no movement or no sound

(Appendix A). All of the toys fit the size of the infant's hand even at the youngest age and are capable of being grasped by a single hand. However, some toys are somewhat more difficult to hold because of their shape or weight.

Data Coding

The software program "Observer" (Noldus ©) was used to code the observations. The options on the program permit precise millisecond coding of prehension and manipulation behaviors. The observations were viewed in real time and in slow motion by two coders, one primary coder and one coder to check for reliability. For prehension observations, reliability between the coders reached a minimum Cohen's Kappa of 92%. For RDBM observations, reliability between the coders reached a minimum Cohen's Kappa of 91%. Analyses of the discrepancies between RDBM observations revealed that coders made disagreements on the type of manipulation being performed during RDBM as opposed to disagreements on the hands involved. Coders were blind to the hand-preference status of the infants.

For prehension, coders determined separately the hand that made the initial reach, the initial contact, and the hand that initially acquired the object. An initial acquisition was defined as the point at which the infant's fingers close around a feature, edge, or area on the toy in a grasp-like motion. In the event of bimanual reaches, the tape speed was slowed so that coders could determine the hand that made the initial grasp. For cases in which both hands attempted to acquire the object within a small time-interval, a distinction criterion of .25 ms was used to distinguish between a single-handed or dual-handed acquisition.

For role-differentiated bimanual manipulation preference, the observations were coded using Observer, for the frequency of RDBM across the 15 presentations and the role in which each hand was engaged (support role or manipulation role) was identified. According to Kimmerle et al. (1995), role differentiation is defined as two hands having different but complementary actions on a toy. One hand facilitates the manipulation actions of the other hand. The non-manipulation actions were operationalized as: supporting (holding up), stabilizing (hang onto), pushing down on, or orienting (turning around) an object. Manipulation actions were defined as: stroking, poking, twirling, pulling, or pushing the object or movable parts of the object. Following the coding method detailed by Kimmerle et al. (1995), in order to be classified as a RDBM, the action must meet specific criteria including:

1. The presence of manual movement. Incidental or brief contacts (less than .3 s) were not considered a manipulation.
2. Manipulations had to be apparent at normal tape speed.

3. Manipulations could involve one or two fingers.
4. Manipulations could also involve the whole hand, the palm, or all the fingers. To be considered as a manipulation, the whole-hand action had to include at least 1 s of object exploration.
5. Role-differentiation could involve a brief single action or a continuous series of actions. Bouts of role-differentiation, regardless of duration, were separated by unimanual actions, other bimanual actions, or 1-s pauses of action.

CHAPTER III

RESULTS

Prehension

In the current data, the percentage of missing observations for prehension was about 9% for the first wave, 4% for the second and third wave, 1% for the fourth wave, 4% for the fifth wave, and 5% for the sixth wave of data collection. Table 1 indicates the number of infants from whom prehension data was observed for each of the six time points. For most of the time points, at least 81 infants provided data. The only exception was at 6 months of age where only 77 out of the 85 infants in the sample provided data.

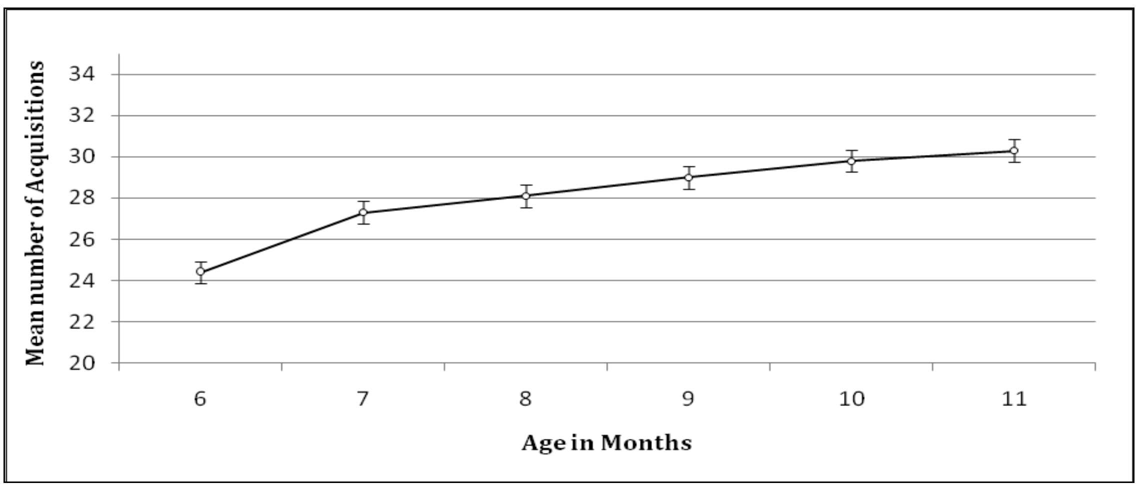
Table 1

Number of infants providing data and number of acquisitions according to age

Age	**Number of Infants Providing Data**	**Acquisitions (SD)**
6	77	24.4 (5.2)
7	81	27.3 (4.9)
8	82	28.1 (4.3)
9	84	29 (4.6)
10	82	29.8 (4.6)
11	81	30.3 (5.3)

Table 1 also provides data for frequency of "acquisitions" per age group. The average number of acquisitions ranged from 24.4 at six months to 30.3 at eleven months. A one-way repeated-measures analysis of variance was conducted to evaluate whether there was a change in the average number of acquisitions across the six age groups. The ANOVA was significant, $F(5, 310) = 16.9$, $p<.000$.. Figure 1 shows the change in average number of acquisitions throughout the 6- to 14-month time period. Follow-up polynomial contrasts indicated a significant linear effect with means increasing over time,, $F(1,62) = 56.01$, $p<.000$. Higher-order polynomial contrasts were nonsignificant.

Figure 1. Change in average number of acquisitions across the age groups



Individual growth modeling techniques were used to analyze the longitudinal data for infant prehension handedness. The proportion of right acquisitions at each age was calculated for each infant by dividing the frequency of right acquisitions by the total number of acquisitions for that specific time point. The proportion of right reaches was modeled for each individual using SAS PROC MIXED, full maximum likelihood method. Multilevel models of change permit the simultaneous analyses of two research questions: (1) a Level 1 (within-person) question focused on how an individual's handedness for prehension changes over time, and (2) a Level 2 (between-person) question focused on how individual changes in handedness for prehension vary across infants (Singer & Willett, 2003). In order to posit an appropriate Level 1 model that describes the changes in hand-use preference of individual infants, we first examined empirical growth trajectories for all 85 infants. Visual inspection of the trajectories (presented in Appendix B) indicated variations in the rate of change. However, the shape of the trajectories roughly appeared similar. That is, the shape of the trajectories appeared linear. Therefore, a linear Level 1 submodel was specified.

Before fitting the model analyzing change, an unconditional means model which partitions and quantifies variation in proportion of right acquisitions across people without regard to time was fit. In the model, there are no predictors at each level. The purpose of the model is to serve as a valuable baseline against which to compare the value of subsequent fitted models. The unconditional means model (UMM) was defined as:

$$\text{(Level-1) PREHENSION}_{ij} = \pi_{0i} + \varepsilon_{ij}$$

$$\text{(Level-2) } \pi_{0i} = \gamma_{00} + \zeta_{0i}$$

The model stipulates that, at level-1, the true individual change trajectory for person i is completely flat, sitting at the intercept $\pi_{0\iota}$. The single part of the level-2 submodel indicates that although flat trajectories may differ in intercept, their average intercept, across everyone in the population, is γ_{00}. Table 2 provides results from fitting the model.

Table 2

Results of fitted model without time

		Parameter	Estimates	Standard Error
Fixed Effects				
π_{0i} (Initial status)	Intercept	γ_{00}	0.61***	0.012
Random Effects				
Level 1	Within-person	σ^2_e	0.04***	0.003
Level 2	In initial status	σ^2_0	0.006*	0.002

~* $p< .05$; *** $p< .005$

Next, an unconditional growth model which includes the introduction of time (i.e. age) was proposed. As mentioned above, based on exploratory analyses a linear level-1 submodel was proposed:

$$\text{(Level-1) PREHENSION}_{ij} = \pi_{0i} + \pi_{1i}(\text{AGE} - 6)_{ij} + \varepsilon_{ij}$$

In level-1, $PREHENSION_{ij}$ represents the proportion of right acquisitions for child *I* at time *j*. Age is centered around 6 months. Temporal recentering simplifies interpretation of the model's parameters (Singer & Willett, 2003). By centering infant age around 6 months, the individual growth parameters have the following interpretations: π_{0j}represents infant *i*'s true proportion of right-handed acquisitions at 6 months of age and π_{1j}represents infant *i*'s true instantaneous change in proportion of right acquisitions. The residual in equation 1, ε_I, represents that portion of infant *i*'s proportion of right acquisitions that is not predicted by his or her age.

The Level 2 (between-person) portion of the multilevel model for change used the individual growth parameters from the within-person (Level 1) submodel as outcomes and enabled us to determine whether infants vary in their initial status and how their hand-use preference for prehension changes during this time period. The Level 2 submodel was:

$$\pi_{0i} = \gamma_{00} + \zeta_{0i}$$
$$\pi_{1i} = \gamma_{10} + \zeta_{1i}$$

In equation 2, γ_{00} represents the population average true initial status (proportion of right acquisitions at 6 months); γ_{10}represents the average true rate of change in proportion of right reaches. The Level 2 submodel also contains stochastic components that allow the value of each infant's growth parameters to be scattered around the population averages.

ζ_{oi} or ζ_{1i} represent those portions of the Level 2 outcomes that remained unexplained. Thus, because the entire multilevel model includes no substantive predictors other than time, each part of the Level 2 submodel simply indicates that an individual growth parameter (either π_{0i} or π_{1i}) is the sum of an intercept and a Level 2 residual (ζ_{oi} or ζ_{1i}). The Level 1 and Level 2 submodels can be combined in the following form:

$$PREHENSION_{ij} = \pi_{0i} + \pi_{1i}(AGE - 6)_{ij} + [\varepsilon_{ij} + \zeta_{0i} + \zeta_{1i}(AGE - 6)_{ij}]$$

The model contains both fixed and random effects. The random components of the model are contained within the brackets in equation 3. Table 2 displays the results of fitting the model.

The fixed effects, γ_{00} and γ_{01}, estimate the starting point and the slope of the population average change trajectory. We reject the null hypothesis for each ($p <$ .001), estimating that the average true change trajectory for PREHENSION has a non-zero intercept of .58 and a non-zero slope of +.014. Figure 2 displays the average fitted growth trajectory based on the model. The figure demonstrates that the average infant shows a greater proportion of right acquisitions, with the proportion slowly increasing, over the 6- to 11-month time period.

Table 3

Results of fitted unconditional growth model

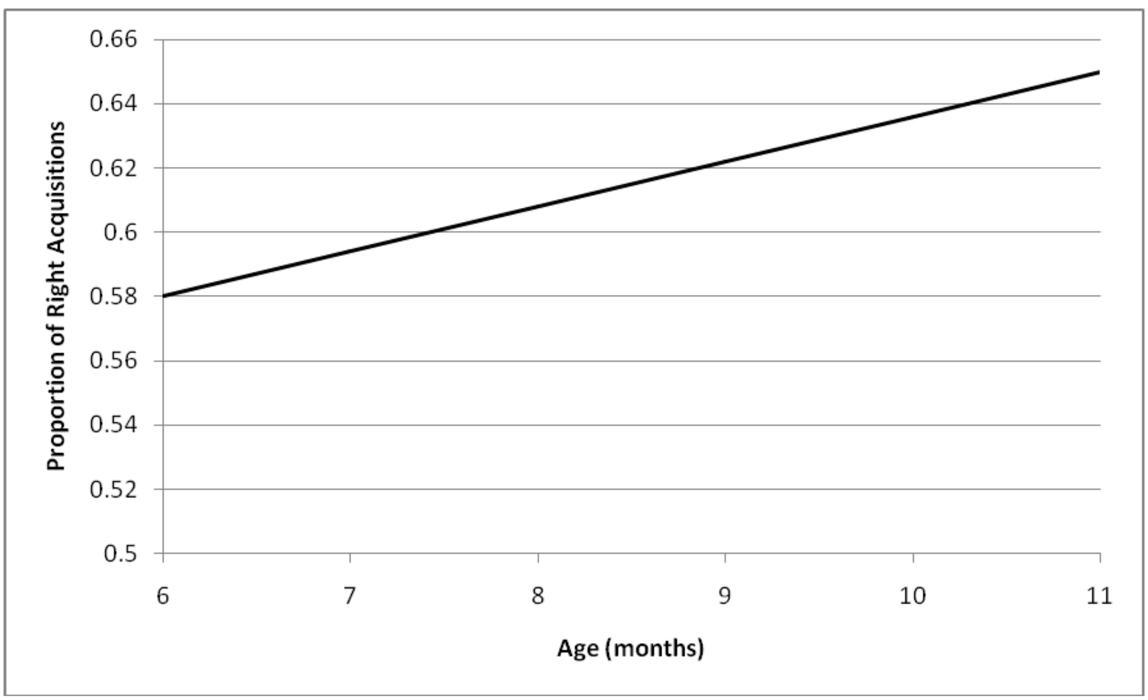
		Parameter	Estimates	Standard Error
Fixed Effects				
π_{0i} (Initial status)	Intercept	γ_{00}	0.58***	0.017
π_{1i} (Rate of change)	Intercept	γ_{01}	0.014***	0.005
Random Effects				
Level 1	Within-person	σ^2_e	0.04***	0.003
Level 2	In initial status	σ^2_0	0.006*	0.002
	In rate of change	σ^2_1	-0.0001	0.0004
	Covariance	σ_{01}	0.0008	0.0006

~* $p< .05$; *** $p< .005$

σ^2_e summarizes the average scatter of an individual's observed outcome values around his or her own true change trajectory. We reject the null hypothesis for this variance component ($p < .001$), a result which suggests important within-person variation remains at Level 1. σ^2_0 assesses the unpredicted variability in true initial status. We reject the null hypothesis and conclude that the estimate, .04, indicates there is non-zero variability in initial status. The parameters for variability in rate of change and the population covariance of the Level 2 residuals were not significantly different from zero. Thus, there was no significant relationship between an infant's initial status and his/her rate of change. Although there appeared to be a large amount of variability in the rates of change based on exploratory analyses, we computed the variance of the slopes and found it to be almost zero. The negative parameter estimate in Table 2 is a result of the program's iteration procedure approaching a boundary constraint on a parameter (i.e. zero for slope variance).

Figure 2

Average fitted growth trajectory for unconditional growth model



RDBM

RDBM handedness status was calculated for each infant by taking the difference between the number of manipulations with the right hand during RDBM and the number of manipulations with the left hand and dividing this difference by the square root of the sum of the right- and left-hand manipulations during RDBM (Michel, Sheu, &Brumley, 2002). Thus, the following formula was used to create a lateralized manipulation score (LMS):

$$LMS = R – L / SQRT (R+L)$$

Based on laws of chance, and an adequate sample size, the infant would use his/her right and left hand with equal probability. If it can be shown that the infant does not use both hands with equal frequency by a difference that deviates significantly, then it can be said that the infant has demonstrated a difference between the two hands that is unlikely to have occurred by chance (Lederer, 1939). Infants with a score less than -1.65 were considered as having a significant left hand-use preference. Infants with a score greater than +1.65 were considered as having a significant right hand-use preference. Infants with a lateralized score greater than -1.65 but less than +1.65 were identified as having no preference for RDBM. These decision points were chosen based on analyses provided in Michel, Sheu, & Brumley (2002). Table 3 displays the results for the number of infants with a hand-use preference for RDBM at 11- and 14-months of age.

Table 4

Hand-use preference for RDBM at 11 and 14 months

	Handedness Group			
Age (months)	**R**	**L**	**NP**	**No data**
11	25	6	50	4
14	47	9	29	0

At 11-months of age, the majority of infants did not display a significant hand-use preference for RDBM. About 62% had no preference for either hand, 31% had a right hand-use preference, and 7% had a left hand-use preference for RDBM. Four infants did not provide data at 11 months because of missed appointments. By 14-months of age, the majority of infants displayed a significant right hand-use preference for RDBM. Approximately 55% had a right hand-use preference, 11% had a left hand use-preference, and 34% hand no preference for RDBM.

A chi-square test for k independent samples was conducted to compare differences between the distributions at 11 and 14 months. The analysis revealed a significant difference between the two age groups, $\chi^2(2) = 12.82$, $p < .001$. Next, a chi-square goodness-of-fit test was conducted to compare each month's distribution to Annett's (1996) estimate of the distribution of RS in the population. According to Annett, RS is a single gene that creates a bias toward right-handedness for the majority of individuals that inherit a right-shift (RS) gene. Absence of the gene results in random processes determining individual handedness. The distribution of handedness for RDBM was compared to the proportions for the human population derived by Annett (1996): RS +/+ (right preference) = .3242, RS +/- (no preference) = .4904, RS -/- (left preference) = .1854. Comparison of these proportions with those obtained by the assessment of RDBM handedness revealed a significant difference at 11 months, $\chi^2(2) = 7.94$, $p < .05$. Comparison of the proportions to the 14-month data also revealed a significant difference $\chi^2(2) = 21.89$, $p < .001$.

A chi-square goodness-of-fit test was also conducted to compare the proportions obtained in the current sample to the distribution identified by an association analysis of Annett's (1970) handedness questionnaire. Annett derived the following proportions for the distribution of handedness in the adult population: right = .666, left = .0445, and mixed (no preference) = .2986. Comparison of these proportions with the results obtained for RDBM at 11 months revealed a significant difference, $\chi^2(2) = 48.27$, $p < .001$. The proportions of RDBM handedness were also significantly different at 14 months, $\chi^2(2) = 8.34$, $p < .05$.

Relationship between Prehension and RDBM Handedness

As identified by the variance components in the fitted multi-level model, there was a significant amount of variation in trajectories for infant prehension hand-use preferences. Observation of these trajectories appeared to reveal several subgroups of hand-use preference. For example, some infants appeared to have no hand-use preference for acquiring objects at 6 months of age, but by 11 months showed a greater likelihood to acquire objects with the right. That is, over time these infants shifted from no difference in use between the two hands for acquiring objects to a greater propensity to acquire objects with the right. Indeed, there were also infants that demonstrated a consistent difference in use between the hands for acquiring objects. For example, some infants displayed a greater likelihood to acquire objects with the right for the entire 6- to 11-month time period. Therefore, several subgroups of hand-use preference for prehension were identified from observation of their trajectories:

1) Infants that demonstrated a consistent right, left, or no hand-use preference across the 6 assessment ages;
2) Infants with a right hand-use preference at 6 months and by 11 months had no hand-use preference or a left hand-use preference;
3) Infants with a left hand-use preference at 6 months and by 11 months had no hand-use preference or a right hand-use preference;
4) Infants with no hand-use preference at 6 months and by 11 months had a right hand-use preference or a left hand-use preference.

Infant were identified as having a preference if their proportion of acquisitions was greater than .60 (right preference) or less than .40 (left preference). Table 4 shows the distribution of hand-use preferences based on the subgroups.

Table 5

Distribution of hand-use preference based on subgroups of prehension preference

Hand-use Preference	Number of Infants	Percent of Infants
Consistent Right	21	25%
No Preference to Right	24	28%
Left to Right	8	9%
Consistent Left	1	1%
No Preference to Left	4	5%
Right to Left	3	4%
Consistent No Preference	12	14%
Right to No Preference	10	12%
Left to No Preference	2	2%

Given the limits of our relatively small sample size, there were not enough infants in each subgroup to draw conclusions about whether the different types of trajectories of infant hand-use preference predicted hand-use preferences for RDBM. Thus, the subgroups were combined to make three main hand-use preference groups: right, left, and no preference. Those infants who demonstrated a consistent right, or changed from no preference to right, or changed from left to right were combined to form the right preference group. Infants who demonstrated a consistent left, or changed from no preference to left, or changed from right to left were combined to form the left preference group. Finally, those infants that consistently had no preference, or changed from right to no preference, or changed from left to no preference were combined to form the no preference group. These three groups were used to determine the relationship between hand-use preferences for prehension and hand-use preferences for RDBM. Table 5 displays the results.

Table 6

Hand-use preference for RDBM in relation to prehension handedness

		RDBM (11 months)		
Prehension	**R**	**L**	**NP**	**No data**
R	13	3	34	3
L	1	2	4	1
NP	11	1	11	1
		RDBM (14 months)		
Prehension	**R**	**L**	**NP**	**No data**
R	28	6	19	0
L	4	1	3	0
NP	15	2	7	0

At 11-months of age, regardless of the infant's hand-use preference for prehension, the majority of infants had no preference for RDBM. Of the 50 infants that provided RDBM data in the right prehension preference group, 26% hand a right hand-use preference for RDBM, 6% had a left hand-use preference, and 68% had no preference at 11 months. By 14-months of age in the right prehension preference group, 53% had a right RDBM preference, 11% had a left hand-use preference, and 36% had no preference. For the infants in the left prehension preference group at 11 months, 14% had a right hand-use preference for RDBM, 29% had a left hand-use preference, and 57% had no preference for RDBM. At 14-months of age, 50% had a right hand-use preference for RDBM, 13% had a left preference, and 37% had no preference. In the no preference prehension group, 48% had a right hand-use preference for RDBM at 11 months, 4% had a left preference, and 48% had no preference. By 14-months of age, 63% had a right preference for RDBM, 8% had a left preference, and 29% had no preference for RDBM.

A separate chi-square was conducted for each of the age groups. Analysis of the expected and observed outcomes at 11 months revealed no significant difference, $\chi^2(4) = 8.77$, $p > .05$.The chi-square for the distribution at 14 months also revealed no significant difference, $\chi^2(4) = .74$, $p > .10.0$

CHAPTER IV

DISCUSSION

The aim of the current study was to examine the relationship between hand-use preferences for prehension and hand-use preferences for RDBM. Previous research with infants has demonstrated that hand-use preferences for reaching predict hand-use preferences for unimanual manipulation (Hinojosa, Sheu, & Michel, 2002). By exhibiting a consistent hand-use preference for reaching for objects, infants create sensorimotor experiences in their exploration of objects in the environment that can contribute to organizational differences between the two hemispheres. These early experiential effects may concatenate into hemispheric differences in the organization of more sophisticated manual skills. Thus, the aim with the present research was to identify a potential predictor of hand-use preference for a skill that emerges late in infancy by identifying consistent hand-use preferences for a skill that emerges early in development.

Although there is considerable debate about the stability of handedness during infancy, reliable hand-use preferences can be identified with longitudinal measurement techniques that take into account task demands, postural constraints, and the motor skill repertoire of the infant (Michel, Sheu, Tyler, & Ferre, 2006). Consistent with previous findings, the results from the model fit here demonstrate a distinct right-shift in the distribution of handedness. That is, on average infants prefer to acquire objects with the right hand and demonstrate an increasing propensity throughout the 6- to 11-month time period to acquire objects with the right hand.

The fitted model also provided information about individual variation. The parameter summarizing within-individual variance, σ^2, suggests that significant variation remains unexplained for individual infant trajectories. This is not surprising given that age has been described as a poor predictor of the state of the nervous system (Wohlwill, 1970). Future models would benefit from the inclusion of time-varying predictors that can be substituted for age at Level 1 of the model. For example, data collection for a future study is currently being conducted in which information about infants' basic motor skills are assessed. Towen (1976) identified a series of items that demonstrate developmental progression during the age period of 6- to 14-months of age. These items can be assessed monthly and could serve as a more valuable predictor of handedness status than age alone.

Analysis of the average number of acquisitions per month revealed significant differences across the age groups. Moreover, there was a significant linear trend indicating that the skill of prehension improves during the 6- to 11-month age period. It is likely that the presence of a consistent hand-use presence may improve or facilitate an infant's ability to acquire objects. Indeed, Kotwica, Ferre, and Michel (2008) demonstrate that the presence of a hand-use preference facilitates an infant's ability to acquire and manage multiple objects. It remains to be determined if this ability differs in any significant pattern between left- and right-handed infants.

One difficulty in drawing comparisons across handedness groups is the limitation of small sample sizes. Infants with a left hand-use preference represent a significantly small portion of the population. Therefore, a large number of infants (~250) are required to make adequate comparisons across groups. In addition, sampling at monthly intervals revealed interesting developmental changes that may not be apparent when sampling occurs at bimonthly intervals. For example, the results revealed groups of infants that remained consistent for prehension handedness, groups of infants that shifted across preference (e.g. from right to left), and groups that initially had no preference and developed a preference by 11 months. Thus, by 11 months an infant may exhibit a hand-use preference; however the means by which he/she reaches this state may involve a quite distinct developmental trajectory from other infants. It is unknown what the consequences of these different developmental trajectories may be. However, it is likely that they may play a role in the organization of manual skills at later ages and the development of cognitive abilities. Infants with a consistent hand–use preference are more likely to store objects than infants without a hand-use preference. Storage has been identified as a skill that serves as the foundation of symbolic representation (Bruner, 1973). Therefore, larger sample sizes are needed to determine the functional significance of different developmental trajectories of handedness.

Another goal of the study was to examine the distribution of hand-use preferences for RDBM at 11- and 14-months of age. RDBM can be identified in infants as early as 7-months of age but it does not become a well-established skill until about 11 to 12 months (Kimmerle, Mick, & Michel). Because the skill requires sophisticated, finely-timed sequences of actions, we did not expect to see a majority of infants with a hand-use preference at an age where the manual action is just beginning to dominate the motor skill repertoire of the infant. Indeed, the results demonstrated that at 11 months an overwhelming majority of infants do not demonstrate a hand-use preference for RDBM. By 14 months, approximately 65% of infants have a hand-use preference with a significant majority of these individuals demonstrating a right hand-use preference. As the skill develops, knowledge of object function, changes in perceptual-motor skill, and comprehension of objects' physical characteristics are likely to combine with developing expertise in control of the two hands to permit expression of the hand-use preference.

The distribution of RDBM handedness was also compared to two theoretical distributions proposed by Annett (Annett, 1996; Annett, 1970). The first, based on Annett's right shift (RS) genetic model, attempts to account for the distribution of handedness in the population by identifying the distribution of an allelic variant that biases an individual to develop a right-hand use preference when the gene is present. The second model examined for the distribution of handedness is based on an association analysis of Annett's 12-item questionnaire. The distribution of handedness for RDBM identified in the current study did not match either of the models. Examination of the cells in the chi-square analysis revealed that the largest contribution to the chi-square was from the cell of individuals observed with a left-preference. Thus, failure to match the distribution may have been a result of too few infants with a left hand-use preference.

Finally, a major goal of the study was to identify a potential predictor of RDBM handedness. The analysis revealed that RDBM handedness appears to be distributed randomly across the different prehension preference groups. Again, failure to identify any significant relationship may be due in large part to the small number of left-handed infants in the sample. At present, it is unknown why the current sample had a significantly lower proportion of left-handed individuals compared to previous samples (Michel, Sheu, Tyler, & Ferre, 2006). However, one possibility may be the development of unimanual manipulation and its relationship to prehension and RDBM. Unimanual manipulation is a skill that emerges after prehension preferences are established but before RDBM becomes established as a dominant skill in the motor repertoire of the infant. Thus, future research would benefit from focusing on how unimanual manipulation preferences may mediate the relationship between prehension preferences and handedness for RDBM.

The current study provides an important contribution to the literature on infant handedness given its relatively large sample. The data revealed interesting patterns of developmental change that can be identified when data are collected longitudinally and at monthly intervals. However, even larger sample sizes are needed in order to conduct the appropriate analyses needed to make comparisons across these potential subgroups of handedness. With the use of longitudinal techniques, sophisticated modeling of data, and careful assessment of different manual skills, we can begin to create a model of lateralization of motor skills that can be used to assess the development of other forms of lateralization.

REFERENCES

Amunts, K., Shlaug, G., Shleicher, A., Steinmetz, H., Dabringhaus, A., Roland, P.E., & Ziles, K. (1996). Asymmetry in the human motor cortex. *Neuroimage,* 4, 216-222.

Amunts, K., Schmidt-Passos, F., Schleicher, A. & Zilles, K. (1997). Postnatal development of interhemispheric asymmetry in the cytoarchitecture of human area 4. *Anatmoy and Embryology*, 196, 393-402.

Annett, M. (1970). A classification of hand preference by association analysis. *British Journal of Psychology*, 61, 303-321.

Annett, M. (1975). Hand preference and laterality of cerebral speech. *Cortex,* 11, 305-328.

Annett, M. (1985). *Left, right, hand and brain: The right shift theory.* Hove, UK: Lawrence Erlbaum Associates Ltd.

Annett, M. (1996). In defense of the right shift theory. *Perceptual and Motor Skills*, 82, 115-137.

Berthier, N.E., & Keen R. (1996). Development of reaching in infancy. *Experimental Brain Research*, 169, 507-518.

Bishop, D.V., Ross, V.A., Daniels, M.S., Bright, P. (1996). The measurement of hand preference: a validation study comparing three groups of right-handers. *British Journal of Psychology,* 87(2), 269-285.

Bryden, M.P., Singh, M., Steenhuis, R.E., & Clarkson, K.L. (1994). A behavioral measure of hand preference as opposed to hand skill. *Neuropsychologia*, 32, 991-999.

Bruner, J.S. (1973). Beyond the information given. New York : W.W. Norton and Co.

Cardoso de Oliveira, S., Gribova, A., Donchin, O., Bergman, H., Vaadia, E. (2001). Neural interactions between motor cortical hemispheres during bimanual and unimanual arm movements. *European Journal of Neuroscience*, 14, 1881-1896.

Cernacek, J. & Podivinski, F. (1971). Ontogenesis of handedness and somatosensory cortical response. *Neuropsychologia*, 9, 219-232.

Corbetta, D. & Thelen, E. (1999). Lateral biases and fluctuations in infants' spontaneous arm movement and reaching. *Developmental Psychobiology,* 34, 237-255.

Coren, S., & Porac, C. (1978). The validity and reliability of self-reported items for the measurement of lateral preference. *British Journal of Psychology*, 69, 207-211.

Curt, F., Maccario, J., & Dellatolas, G. (1992). Distributions of hand preference and hand skill asymmetry in preschool children: Theoretical implications. *Neuropsychologia,* 30, 27-34.

De Gennaro, L. et al. (2004). Handedness is mainly associated with an asymmetry of corticospinal excitability and not of transcallosal inhibition. *Clinical Neurophysiology*, 115, 1305-1312.

Dehaene-Lambertz, G., Dehaene, S. & Hertz-Pannier, L. (2002). Functional neuroimaging of speech perception in infants. *Science*, 298, 2013-2015.

Diamond, A. (1991). Neuropsychological insight into the meaning of object concept development. In S. Carey & R. Gelman (Eds.), *The epigenesis of mind: Essays on biology and cognition.* Hillsdale, NJ: Erlbaum.

Dragovic, M. (2004). Categorization and validation of handedness using latent class anlaysis. *Acta Neuropsychiatrica*, 16, 212-218.

Dragovic, M. & Hammond, G. (2007). A classification of handedness using the Annett hand preference questionnaire. *British Journal of Psychology*, 375-387.

Duque, J., Mazzocchio, R., Dambrosia, J., Murase, N., Olivier, E. & Cohen, L.G. (2005). Kinematically specific interhemispheric inhibition operating in the process of generation of a voluntary movement. *Cerebral Cortex*, 15, 588-593.

Ellenberg, L. & Sperry, R.W. (1980). Lateralized division of attention in the commissurotomized and intact brain. *Neuropsychologia*, 18, 411-418.

Fagard, J., & Corroyer, D. (2003). Using a continuous index of laterality to determine how laterality is related to interhemispheric transfer and bimanual coordination in children. *Developmental Pyschobiology*, 43, 44-56.

Fagard, J. & Lockman, J.J. (2005). The effect of task constraints on infants (bi)manual strategy for grasping and exploring objects. *Infant Behavior and Development*, 28, 305-315.

Fagard, J., Hardy, I., Kervella, C., & Marks, A. (2001). Changes in interhemispheric transfer and the development of bimanual coordination. Journal of Experimental Child Psychology, 80, 1–22.

Fagard, J. (1998). Changes in grasping skills and the emergence of bimanual coordination during the first year of life. *Clinics in Developmental Medicine*, 147, 123-143.

Fagard, J. & Jacquet, D.Y. (1989). Onset of bimanual coordination and symmetry versus asymmetry of movement. *Infant Behavior and Development*, 12, 229-235.

Farber, D. A., & Knyazeva, M. G. (1991). Electrophysiological correlates of interhemispheric interaction in ontogenesis. In G. Ramaekers & C. Njiokiktjien (Eds.), Pediatric behavioral neurology (Vol. 3, pp. 86–99). Amsterdam: Suyi.

Fetters L, & Todd J (1987) Quantitative assessment of infant reaching movements. *Journal of Motor Behavior*, 19, 147–166.

Flowers, K. (1975). Handedness and controlled movement. *British Journal of Psychology*, 66(1), 39-52.

Fink, G.R. Marshall, J.C., Halligan, P.W., Frith, C.D., Driver, J., Frackowiak, R.S.J., Dolan, R.J. (1999). The neural consequences of conflict between intention and the senses. *Brain*, 122, 497-512.

Friston, K. (1998). The disconnection hypothesis. *Schizophrenia Research*, 30, 115-125.

Gabbard, C., & Rabb, C. (2000). What determines choice of limb for unimanual reaching movements? *Journal of General Psychology*, 127(2), 178–184.

Gazzaniga, M., Bogen, J.E., & Sperry, R.W. (1967). Dyspraxia following division of the cerebral hemispheres. *Archives of Neurology,* 16, 606-612.

Gazzaniga, M. (2000). Cerebral specialization and interhemispheric communication: Does the corpus callosum enable the human condition. *Brain*, 123, 1293-1326.

Geffen, G.M., Jones, D.L. & Geffen, L.B. (1994). Interhemispheric control of manual motor activity. *Behavioral Brain Research*, 20, 131-140.

Goldfield, E.C., & Michel, G.F. (1985). Spatiotemporal linkage in infant interlimb coordination. *Developmental Psychobiology*, 19(3), 259-264.

Haaland, K.Y., Harrington, D.L., & Knight, R.T. (2000). Neural representations of skilled movement. *Brain,* 123, 2306-2313.

Haaland, K.Y., Elsinger, C.L., Mayer, A.R., Durgerian, S. & Rao, S.M. (2004). Motor Sequence complexity and performing hand produce differential patterns of hemispheric lateralization. *Journal of Cognitive Neuroscience*, 16, 621-636.

Habib, M. (2000). The neurological basis of developmental dyslexia. *Brain*, 123, 2373-2399.

Hagelthorn, K. M., Brown, W. S., Amano, S., & Asarnow, R. (2000). Normal development of bilateral field advantage and evoked potential interhemispheric transmission time. Developmental Neuropsychology, 18, 11–31.

Harris, L.J., & Carlson, D.F., (1993). Hand preference for visually-guided reaching in human infants and adults. In J.P. Ward & W.D. Hopkins (Eds.), *Primate* *laterality: Current behavioral evidence of primate asymmetries* (pp.285-305). New York: Springer-Verlag.

Hazeltine, E., Diedrichsen, J., Kennerley, S.W., Ivry, R.B. (2003). Bimanual cross-talk during reaching movements is primarily related to response selection, not the specification of motor parameters. *Psychological Research,* 67, 56-70.

Hinojosa, T. Sheu, C.F., Michel, G.F. (2003). Infant hand-use preferences for grasping objects contributes to the development of a hand-use preference for manipulating objects. *Developmental Psychobiology,* 43, 328-334.

von Hofsten, C. (1991). Structuring of early reaching movements: a longitudinal study. Journal of Motor Behavior, 23, 280–292.

Holowka, S., & Petitto, L.A. (2002). Left hemisphere cerebral specialization for babies while babbling. *Science*, 297, 1515.

Janssen, J.P. (2004). Evaluation of empirical methods and methodological foundations of human left-handedness. *Pereceptual and Motor Skills,* 98, 487-506.

Jeannerod, M. (1981). Intersegmental coordination during reaching at natural visual objects. *Attention and Performance IX*, J. Long and A. Baddeey (Eds), 153-168, Erlbaum, Hillsdale.

Kelso, J.A.S., Putnam, C.A., & Goodman, D. (1983). On the space-time structure of human inter-limb coordination. *Quarterly Journal of Experimental Psychology*, 35(A), 347-375.

Kimmerle, M., Mick, L.A., Michel, G.F. (1995). Bimanual role-differentiated toy play during infancy. *Infant Behavior and Development*, 18, 299-307.

Kimura, D. (1993). Neuromotor Mechanisms in Human Communication. Oxford: Oxford University Press.

Kimura, D., & Archibald, Y. (1974). Motor functions of the left hemisphere. *Brain*, 97, 337-350.

Kimura, D., & Watson, N. (1989). The relation between oral movement control and speech. *Brain & Language*, 37, 565-590.

Kolb, B., & Gibb, R. (2001). Early brain injury, plasticity, and behavior. In Nelson, C.A., Luciana, M. (Eds.) Handbook of Developmental Cognitive Neuroscience, Cambridge, MA: MIT Press, 175-190.

Kotwica, K.A., Ferre, C.L., & Michel, G.F. (2008). Relation of stable hand-use preferences to the development of skill for managing multiple objects from 7 to 13 months of age. *Developmental Psychobiology*, 50, 519-529.

Lamantia, A. S., & Rakic, P. (1984). The number, size, myelinization, and regional variation of axons in the corpus callosum and anterior commissure of the developing rhesus monkey. Society for Neuroscience Abstracts, 10, 267–277.

McCormick, C.M., & Maurer, D.M. (1988). Unimanual hand preferences in 6-month-olds; consistency and relation to familial-handedness.

McManus, I.C. (1985). Right- and left-handed skill: Failure of the right shift model. *British Journal of Psychology*, *76*, 1-16.

Michel, G.F., & Harkins, D.A. (1986). Postural and lateral asymmetries in the ontogeny of handedness during infancy. *Developmental Psychobiology*, 19, 247-258.

Michel, G.F., Ovrut, M.A., & Harkins, D.A. (1986). Hand-use preference for reaching and object manipulation in 6- through 13-month-old infants. *Genetic, General, and Social Psychology Monographs*, 111, 407-429.

Michel, GF. A neuropsychological perspective on infant sensorimotor development. In Lipsitt, LP, Rovee-Collier, CK, (Eds.) Advances in infancy research, vol. 5. Norwood, NJ: Ablex Pub. Corp. 1988:1-37.

Michel, G. F. (1998). A lateral bias in the neuropsychological functioning of human infants. Developmental Neuropsychology , 14, 445-469.

Michel, G.F., Sheu, C.F., & Brumley, M.R. (2002). Evidence of a right-shift factor affecting infant hand-use preferences from 7 to 11 months as revealed by latent class analysis. *Developmental Psychobiology*, 40, 1-13.

Michel, G.F. (2002). Development of infant handedness. In D.J. Lewkowicz and R. Lickliter (Eds.) *Conceptions of Development*. New York: Psychology Press. 165-186.

Michel, G.F. & Moore, C.M. (1995). Developmental Psychobiology: An interdisciplinary science. Cambridge, MA: MIT Press.

Michel, G.F., Sheu, C.F., Tyler, A.N., Ferre, C.L. (2006). The Manifestation of infant hand-use preferences when reaching for objects during the seven- to thirteen-month age period. *Developmental Psychobiology*, 48, 436-443.

Netz, J., Ziemann, U. & Homberg, V. Hemispheric asymmetry of transcallosal inhibition in man. *Experimental Brain Research*, 104, 527-533.

Peters, M. & Murphy, K. (1992). Cluster analysis reveals at least three, and possibly five distinct handedness groups. *Neuropsychologia***,** 30(4) 373-380.

Piek, J.P. (2002). The role of variability in early motor development. *Infant Behavior and Development*, 25, 452-465.

Ramsay, D. S., Campos, J. J., & Fenson, L. (1979). Onset of bimanual handedness in infants. *Infant Behavior and Development,* 2, 69-76.

Ramsay, D.S. (1980). Beginnings of Bimanual Handedness and Speech in Infants. *Infant Behavior and Developmen.,* 3, 67-77.

Ramsay, D.S. (1984). Onset of duplicated syllable babbling and unimanual handedness in infancy: evidence for developmental change in hemispheric specialization? *Developmental Psychology*, 20, 64-71.

Ramsay, D.S., & Campos, J.J., & Fenson, L. (1979). Onset of bimanual handedness in infants. *Infant Behavior and Development*, 2, 69-76.

Ramsay, D.S., & Weber, S.L. (1986). Infants' hand preference in a task involving complementary roles for the two hands. *Infant Behavior and Development*, 2, 69-76.

Ransil, B.J., and Schatcher, S.C. (1994). Test-retest reliability of the Edinburgh Handedness Inventory and Global Handedness preference measurements, and their correlation. *Perceptual Motor Skills,* 79, 1355- 1372.

ROSE, S.A.(1984). Developmental changes in hemispheric specialization for tactual processing in very young children: Evidence from cross-modal transfer. *Developmental Psychology*, 20, 568-574.

Sainburg, R.L. (2002). Evidence for a dynamic-dominance hypothesis of handedness. *Experimental Brain Research*, 142, 241-258.

Salamy, A. (1978). Commissural transmission: Maturational changes in humans. Science, 200, 1409–1411.

Schulter, N.D., Rushworth, M.F., Passingham, R.E. & Mills, K.R. (1998) Temporary interference in human lateral premotor cortex suggest dominance for the selection of movements. A study using transcranial magnetic stimulation. *Brain,* 121, 785-799.

Shabbott, B.A., & Sainburg, R.L. (2008). Differentiating between two models of motor lateralization. *Journal of Neurophysiology*, in press.

Sergent, J. (1982). The cerebral balance of power: Confrontation or Cooperation. *Journal of Experimental Psychology: Human Perception and Performance*, 8 (2), 253-272.

Serrien, D.J., Ivry, R.B. & Swinnen, S.P. (2006). Dynamics of hemispheric specialization and integration in the context of motor control. *Nature Reviews: Neuroscience*, 7(2), 160-167.

Singer, J.D., & Willett, J.B. (2003). Applied longitudinal data analysis; Modeling change and event occurrence. Oxford, England: Oxford University Press.

Steenhuis, R.E. and Bryden, M.P. (1999). The relation between hand preference and hand performance: What you get depends on what you measure. *Laterality,* 4(1), 3-26.

Thelen, E., Corbetta, D., Kamm, K., Spencer, J.P., Schneider, K., & Zernicke, R.F. (1993). The Transition to reaching: Mapping intention and intrinsic dynamics. *Child Development,* 64, 1058-1098.

Thelen, E., Corbetta, D., & Spencer, J.P. (1996). Development of reaching during the first year: Role of movement speed. *Journal of Experimental Psychology: Human Perception and Performance*, 22, 1059-1076.

Touwen, B. (1976). Neurological Development in Infancy. Latham, Suffolk; The Lavenham Press LTD.

Wohlwill, J.F. (1970). The age variable in psychological research. *Psychological Review*, 77(1), 49-64.

Wolff, PH, Michel, GF, & Ovrut, MR. (1990). Rate and timing precision of motor coordination in Developmental Dyslexia. Developmental Psychology, 26, 82-89.

Vauclair, J. (1993). Tool use, hand cooperation and the development of object manipulation in human and non-human primates. In A. F. Kalverboer, B. Hopkins, & R. Geuze (Eds.), *Motor development in early and later childhood: Longitudinal approaches.* Cambridge: Cambridge University Press, 205-216.

Verfaellie, M. & Heilman, K.M. (1990). Hemispheric asymmetries in attentional control : Implications for hand preference in sensorimotor tasks. *Brain and Cognition,* 14, 70-80.

Volkman, J., Schnitzler, A., Witte, O.W., & Freund, H.-J. Handedness and asymmetry of hand representation and human motor cortex. (1998). *Journal of Neurophysiology*, 79, 2149-2154.

Verstynen, T.D., Diedrichsen, J., Albert, N., Aparicio, P. & Ivry, R.B. (2005). Ipsilateral motor cortex activity during unimanual hand movements relates to task complexity. *Journal of Neurophysiology*, 93, 1209-1222.

APPENDIX A. RDBM TOYS

APPENDIX B. INDIVIDUAL GROWTH TRAJECOTIRES